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ORIGINAL PAPER

Hydrothermal Carbonisation of Empty Palm Oil Fruit Bunches: Laboratory Trials, Plant Simulation, Carbon Avoidance, and Economic Feasibility

Jan Stemann · Berit Erlach · Felix Ziegler

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Abstract Empty fruit bunches (EFB) from the production of palm oil constitute a significant and increasingly problematic waste stream. Direct firing is hindered by a water content of 65 %. This paper investigates hydrothermal carbonisation (HTC) as one method of upgrading EFB waste to an exportable fuel. We first undertook bench experiments using EFB from Sumatra, Indonesia. The reactor was operated at 220 °C and the product was dewatered with a laboratory piston press to a water content of 32–37 %. The resulting dried HTC coal has an HHV of 28 MJ/kg and the process achieves an energetic yield of 73 %. If the process water is reused, the yield increases to 77 %. Between 10 and 80 % of the inorganic compounds remain dissolved in the process water. These results are used to calibrate a simulation model of an industrial scale HTC plant, using *Aspen Plus* software. Investment and operating costs are estimated for plant capacities of 0.04–0.1 megatonnes per year. 16 kJ of electricity and 67 kJ of boiler fuel are required for each MJ of EFB processed. The landed cost in Europe, with shipping, is 7.9–9.7 €/GJ. Avoided greenhouse gas emissions can improve the economics: EFB are routinely dumped and release methane and the HTC coal can replace bituminous coal in power stations. The avoided net emissions are 190 and 100 kg CO_{2eq}/GJ of HTC coal for avoided methane and avoided carbon dioxide, respectively.

Keywords Biomass · Upgrading · Solid biofuel · Plant simulation · Carbon avoidance · Economic feasibility

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J. Stemann (✉) · B. Erlach · F. Ziegler
Department of Energy Engineering,
Technische Universität Berlin, Marchstr. 18, 10587 Berlin,
Germany
e-mail: jan.stemann@tu-berlin.de

Introduction

Palm Oil Production

World palm oil production amounted to 45 million t crude palm oil in 2009, with Indonesia (44 %) and Malaysia (43 %) being the main producers. Relatively high yields and low production costs have led to a sharp increase in output. Production in Indonesia increased threefold between 2000 and 2009 [1]. However, in consequence greenhouse gas emissions and the loss of ecological diversity due to primary rainforest deforestation for new oil palm plantations become major issues. A sustainable palm oil industry depends on improving land use practice, land use change, fruit bunch processing, the utilization of side products, and plantation management [6]. In this paper we focus on the utilization of empty fruit bunches (EFB), a significant waste stream from the production process, as an alternative fuel.

The production of one tonne of crude palm oil requires approximately five tonnes of fresh fruit bunches (FFB) and produces 3 tonnes of liquid palm oil mill effluent (POME) and 1.9 tonnes of solid biomass waste, namely EFB, mesocarp fibres (the residue of the fruit flesh after the oil has been pressed out), shell, and kernel [2]. Table 1 summarizes these waste streams per tonne of FFB and notes their energy content. The kernel is transported to the kernel crushing plant to produce palm kernel oil [2]. Part of the fibres and shell are used as boiler fuel to cover the energy demand of the palm oil mill. The boiler produces steam at approx. 17–25 bar, which is expanded in a steam turbine to 3–4 bar [3, 4]. The expanded steam is used for sterilization of the FFB. The electricity demand of approximately 20 kWh per tonne of FFB [2] is covered by the steam turbine. On total, the waste products contain more energy than required for the operation of the palm oil mill. While excess fibres and shells are commonly sold [2], EFB and POME impose a waste problem. Using all the waste biomass for on-site heat and power generation is often not feasible since many palm oil mills are not grid-connected and cannot sell their surplus electricity [5]. For example, 6 out of 12 Malaysian palm oil mills analyzed by [2], are grid independent. Besides, EFB are poorly suited as a boiler fuel due to their high moisture of approximately 65 % [6], high ash and potassium content [7] and low ash sintering temperature (620 °C) [4]. POME often is stored in open ponds and releasing methane into the atmosphere. EFB are either used for mulching within the oil palm plantation or simply dumped. Heaps deeper than 5 m generate and release methane [4]. Methane from POME and EFB dumping sites constitute significant greenhouse gas emissions in the palm oil production. Mulching with EFB returns minerals to the plantation, improves the soil structure, increases moisture retention, stimulates root growth, and decreases leaching and soil erosion on steep land [8]. However, mulch also has several downsides, namely attracting harmful beetles, snakes [6], and *Ganoderma bominense*, a fungi which may cause stem rot in oil palm trees [9]. Water pollution by residual oil and high transportation and distribution cost also present issues for EFB mulching [9]. Therefore, alternative ways to treat EFB are discussed, namely composting [6], biogas production [4], and producing combustible briquettes [7]. Another option is the use of hydrothermal carbonisation (HTC), which is discussed in this paper.

Hydrothermal Carbonisation

In the HTC process, biomass is covered with water and heated to 180–250 °C in a pressure vessel. The process is particularly suitable for wet biomass. Within some hours at elevated pressure (e.g. 20 bar) the biomass is converted into the so-called HTC coal. Because of its chemical similarity to lignite, the solid product can be used as substitute fuel. Indeed, HTC can be regarded as a biomass pretreatment technology similar to torrefaction [10]. One important advantage of HTC coal is that, for most types of biomass, it can be dewatered mechanically to a water content of 30–40 % compared to 65 % for raw EFB [6]. In order to use the solid product as a fuel in combustion or gasification, extensive dewatering is crucial in order to avoid energy intensive drying. Moreover, the quality of the HTC coal as fuel as compared to the raw material is improved due to its higher calorific value, and its handling and storage properties. In addition, inorganic substances migrate to the process water, which reduces the ash content of the product and allows for the recovery of nutrients.

HTC is a young technology. The first pilot plants are being tested but there is no long-term experience and no full-scale modern plants have been built.

Scope of This Paper

This paper examines the potential of hydrothermal pretreatment of EFB, a widely unused waste biomass, in order to produce a fuel with enhanced properties. We first performed laboratory scale experiments to determine physical and chemical changes, yields and elemental balances. We then used these results to build and calibrate a plant model in order to assess the auxiliary energy demand and investment costs of an industrial scale HTC plant. Finally we calculated the production costs of HTC coal pellets and the GHG avoidance costs. The paper reports on all three steps.

Current European Union policy targets for renewable energy and for GHG emission reductions have led to a growing demand for industrial wood pellets and sourcing from outside the EU is required [11]. Consequently the local production of HTC coal pellets in Indonesia and the export of pellets to Europe is regarded as an economically promising option and therefore is examined in this paper.

Experiments

Experimental Strategy

Yuliansyah et al. [12] have investigated the hydrothermal treatment of oil palm fronds and trunks over a temperature range from 200 to 350 °C. Energy yields correlate negatively with temperature and ranged from 72 to 56 % in these experiments. Inoue [13] proposed HTC of EFB as a fuel pre-treatment method and also performed experiments over a wide range of temperatures. In our experiments, we

Table 1 Palm oil mill waste streams, per tonne fresh fruit bunches [2], moisture content from [3, 7]

	Mass (wet) (kg)	Mass (dry) (kg)	Moisture (%)	HHV (dry) (MJ/kg)	Energy, total (MJ_{HHV})	Boiler fuel (MJ_{HHV})	Remainder (MJ_{HHV})
Empy fruit bunches	230	81	65	21.3	1716		1716
Mesocarp fibres	120	72	40	19.6	1408	1200	208
Shell	69	62	10	21.8	1349	578	771
Methane from palm oil mill effluent		7.9			437		437

examined dewatering characteristics and tried to increase the energetic yield by four means: (1) Temperature is a sensitive parameter for HTC [13, 14]. In general, a higher temperature promotes a higher calorific value and the destruction of functional groups, and thus results in better dewatering characteristics. On the other hand, more waste gas is formed and the energetic yield is lower. In our experiments we chose a mid-range temperature of 220 °C. (2) For lignin feedstock, a longer residence time increases the solid yield by recondensation of dissolved substances [15]. We therefore chose a reaction time of four hours, under the assumption that this should slightly increase the solid yield, and still allow for reasonable throughput at an industrial scale. (3) A greater dilution of biomass with water facilitates handling of biomass but also promotes the solvolysis of organic compounds. Thus we chose a minimal water to biomass ratio of 5, however the biomass had to be completely covered with water. (4) Even at rather high solid loads, almost 20 % of the carbon remains dissolved in the liquid. A series of experiments was performed in which the process water was partly recirculated. In this way the amount of waste water can be reduced and the carbon yield in the solid rises [16].

A mixed sample of EFB from the palm oil production process was collected at a palm oil mill in the district of Benkulu-Utara, Sumatra, Indonesia. The biomass was dried on site to constant mass at 105 °C.

Processing

The biomass was shredded to 1-10 mm particle size. 20 g of dry and well mixed biomass was covered with 100 g of water and was placed in a Berghof BR-200 reactor with a 200 mL PTFE liner. The reactor was purged with nitrogen. The temperature was controlled by a PID controller. The reactor took 35 min to reach 180 °C and 70 min in total to reach 220 °C. Then it was kept at 220 °C for four hours. Total pressure reached 28 bar during the reaction. Cooling from 220 °C to 180 °C took 25 min.

Two experimental series were conducted, as indicated in Table 2. In the first case, referred to as *HTC-Ref*, de-ionized water was added to the biomass. This experiment was repeated three times. In the second case de-ionized water was partly substituted by process water from each previous experiment in order to simulate process water recirculation. Therefore 37.14 g of de-ionized water (to simulate a water content of the biomass of 65 %) and 62.86 g of process water (to reach a total of 100 g) were added to the biomass. In order to reach equilibrium, this experiment was repeated 10 times and is referred to *HTC-Recirc*. For statistical reasons, samples from the last three runs (eight, nine, ten) were aggregated.

Table 2 Overview of experiments (uncertainties in parenthesis)

	HTC-Ref	HTC-Recirc
De-ionized water (g)	100.00 (0.01)	37.14 (0.01)
Process water (g)	0.00 (0.01)	62.86 (0.01)
No. of experiments	3	10

Analysis of the Products

After cooling to room temperature, one reactor valve was completely opened for 3 min and the vented gas collected in a sample bag. Its volume was determined.

The solid and liquid products were separated by vacuum filtration with an 8 µm cellulose paper filter. The solid phase in the filter paper was then transferred to a laboratory piston press and the solid was mechanically dewatered at 10 bar for 5 min. The solid then was removed from the filter paper and was dried at 105 °C for 24 h for further analysis.

Ultimate analysis (C, H, N, S) of the dry solid substances was carried out with a Vario EL III elemental analyzer (elementar analysensysteme GmbH). Ash was determined according to EN 14775. The remaining mass was assumed to be oxygen. The HHV and the LHV were derived from its elemental composition [17, 18] and the volatile matter was determined according to DIN 51720. The ash composition was determined with ICP-OES (Varian, Mod. 720-EF, axial torch) after microwave digestion with nitric acid and hydrogen peroxide.

Total organic carbon (TOC) in the water was measured according to EN 1484-H3. The pH of the liquid was determined with a digital probe. The liquid phase was analyzed by HPLC. Therefore 20 µL of sample was injected to 0.01 N sulphuric acid at 0.6 mL/min in a nucleogel sugar column (Macherey–Nagel 810 h, 300 mm × 78 mm) at 80 °C. The sample was detected by an UV-detector at 254 nm and retention times were compared with standard solutions.

The gas composition was analyzed with a HP5890 with packed columns (molesieve and a Porapak QS column, 2 m × 1/8") and a TCD detector.

Mass and carbon recovery in the experiments was 97 % with regards to the biomass. The remainder was presumably lost during the handling of the samples or leakage from the pressurized reactor. Elemental recovery rates ranged between 103 % for K and 77 % for P.

The energetic yield η is calculated according to Eq. 1 by multiplication of the mass yield ($m_{HTC\ dry}/m_{BM\ dry}$) by the ratio of the calorific values of the HTC coal HHV_{HTC} and the biomass HHV_{BM}:

$$\eta = \frac{m_{HTC,dry}}{m_{BM,dry}} \cdot \frac{HHV_{HTC}}{HHV_{BM}} \qquad (1)$$

The energetic yield on a wet basis is calculated by substituting the dry masses by wet masses and by substituting the HHVs by the LHVs on a wet basis.

Experimental Results

Solid Phase

Fuel characteristics of the produced HTC coal are described via proximate and ultimate analysis and are depicted in Table 3. It can be noted that the HTC coal can be dewatered to a large extent. Due to the rise of the carbon content the fraction of volatile matter in the HTC coal is reduced and the higher heating value (HHV) is increased by about 30 %. There is a significant influence of process water recirculation which will be discussed in detail in chapter 3.3.

For use as a fuel, the amount of water relative to the amount of fuel is especially important which explains why the lower heating value (LHV) of the coal increases threefold compared to the biomass when calculated on a wet basis. The energetic yield is 70–80 % when calculated using the HHV, with the major loss being dissolved organic substances. However, for the use as a fuel, the energetic yield based on the LHV is the more relevant figure. It can be higher than 100 % when the effect that less water has to be evaporated completely compensates the losses of the process. A complete energy balance also accounts for the auxiliary energy consumption and this is done by a plant simulation in the next section.

In general, a higher reaction temperature induces a higher carbon content and better dewatering characteristics, but at the expense of a lower energetic yield. Optimal reaction conditions therefore depend on the overall conversion and usage chain.

Table 3 Characterization of the solid: proximate analysis, ultimate analysis, mass yield, calorific values and energetic yields (mean values with uncertainties in parenthesis)

	EFB	HTC-Ref	HTC-Recirc
Proximate analysis			
Moisture (wt%)	0.65[a]	0.37 (0.00)	0.32 (0.01)
Ash (dry) (wt%)	4.52	3.00 (0.21)	3.62 (0.25)
Volatile matter (dry) (wt%)	77.4[b]	64.3 (0.70)	65.5 (0.70)
Ultimate analysis			
C (wt% (dry))	49.18	63.96 (0.19)	64.34 (0.38)
H (wt% (dry))	7.00	6.63 (0.06)	6.92 (0.04)
N (wt% (dry))	0.64	0.74 (0.03)	0.83 (0.02)
S (wt% (dry))	0.07	0.08 (0.02)	0.07 (0.00)
O (wt % (dry))	38.59	25.64 (0.12)	24.22 (0.35)
Mass yield (dry) (%)	–	56.6 (0.4)	58.6 (0.5)
C yield (%)	–	73.6 (0.6)	76.7 (0.5)
HHV(dry) (MJ/kg)	21.33	27.43 (0.13)	28.03 (0.19)
LHV (wet) (MJ/kg)	5.27	15.22 (0.04)	17.24 (0.37)
Energetic yield (HHV) (%)	–	72.7 (0.2)	77.0 (0.6)
Energetic yield (LHV) (%)	–	93.5 (0.6)	99.7 (0.4)

[a] Mean water content of empty fruit bunches after steam sterilization [6]

[b] According to [19]

The change in molar H/C and O/C ratios is depicted in Fig. 1 in a van Krevelen diagram. It can be noted that the ratios of H/C and O/C of HTC coal are lower than those of raw EFB and thus the concentration of C increases. For comparison, the results of experiments with poplar wood at the same reaction conditions are given, too. The hydrogen concentration of both raw EFB and the resulting HTC coal is rather high compared to other types of biomass which explains the relatively high calorific value. This may be due to traces of oil from the production process.

Interestingly the reaction of both EFB and wood show a similar pattern concerning the relative change of H/C and O/C where d(H/C)/d(O/C) = 1.6. The main reaction pathways of HTC are hydrolysis, dehydration, decarboxylation, polymerization and aromatization [14]. The van Krevelen diagram allows for depicting the principal reactions of decarboxylation and dehydration as straight lines [20]. Figure 1 suggests that dehydration is the dominating reaction accompanied by some decarboxylation. In fact some carbon dioxide and water are formed during the reaction but a detailed analysis must also take dissolved organic substances into account which are equally important.

We measured a bulk density of HTC-coal pellets of 685 kg/m^3, similar to that of wood pellets. For raw EFB, a bulk density of 340 kg/m^3 is reported [9]. The energy content of the HTC-coal pellets (at 10 % moisture) is increased by a factor of 3.4 on a mass basis and by a factor of 6.8 on a volume basis, compared to the raw EFB.

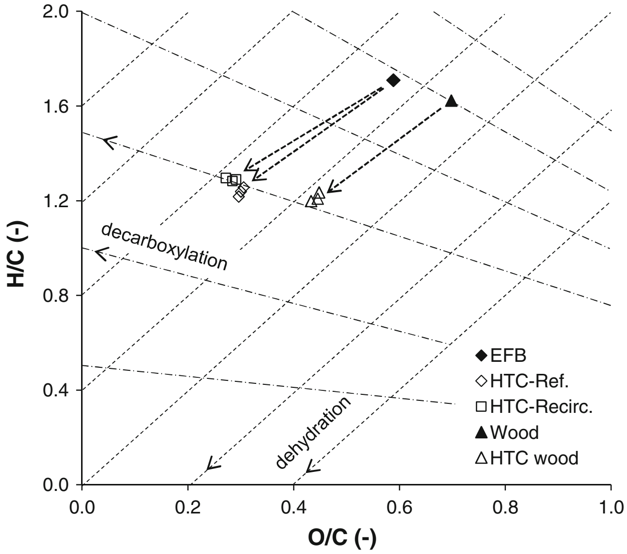

Fig. 1 Van Krevelen diagram with molar H/C and O/C ratios for raw EFB and wood and HTC coal from EFB and wood at the same reaction conditions

Gas and Liquid Phase

Gas forms during the process and consists of mainly carbon dioxide with some carbon monoxide. Gas yields are depicted in Table 4. About five percent of the carbon in the parent biomass is recovered in the gas phase.

More important, however, is the liquid phase where about 18 % of the carbon in the biomass is dissolved. This is significantly more than for poplar wood (13 %) at the same reaction conditions, which may be explained by a higher hemicellulose and lower lignin content of EFB compared to poplar wood. Table 5 lists the concentrations and yields of the dissolved substances which were quantified by HPLC analysis. Especially organic acids are present in high concentrations. The pH of the liquid is 3.6. The influence of water recirculation on the composition is significant and is discussed next.

Process Water Recirculation

A comparison between the carbonisation of EFB with de-ionized and with recirculated process water indicates a rise of the concentration of TOC in the liquid product. The concentration is depicted over the number of recirculations in Fig. 2. Equilibrium is reached after about 5 cycles and with a concentration twice as high as in the reference experiments. Yet, as the amount of waste water is reduced by recirculation, the total amount of carbon dissolved is only 13 % compared to 18 % in the reference case.

Interestingly, the yield of acetic acid in the liquid remains constant in the case of recirculation. This means that its concentration augments in comparison to the TOC (see Table 5) which may facilitate water treatment. Yet the pH of 3.6 remains unchanged despite of a higher concentration of organic acids.

Table 4 Gas yields (g of specific gas per kg of dry biomass)

	CO_2 (g/kg)	CO (g/kg)	CH_4 (g/kg)	H_2 (g/kg)	C yield (g/kg)
HTC-Ref	84	4.1	0.02	0.0	44
HTC-Recirc	93	7.5	0.03	0.1	52

The carbon concentration in the solid and the solid mass yield rise. Thus compared to the reference case the C yield increases by 3 % and the energetic yield rises significantly, too (Table 3). Presumably this is a result of further polymerization of dissolved organic substances. Three quarters of the decrease of the carbon in the liquid phase are compensated by a rise of C in the HTC coal and the remainder by an increase of carbon in the gas phase. From Fig. 1 it can be noted that the hydrogen concentration and H/C increase, which results in an even higher calorific value. The lower oxygen concentration may indicate a lower amount of functional groups and can thus explain the better dewatering characteristics in the case of process water recirculation.

Ash and Nutrients

In the proximate analysis in Table 3 the ash concentration of the raw feedstock and the HTC coal is given. For de-ionized and process water the ash concentration is reduced to 66 and 80 % respectively, in comparison to raw EFB. However, as the mass yield is less than 60 %, total ash yields are only 38 % and 47 % respectively.

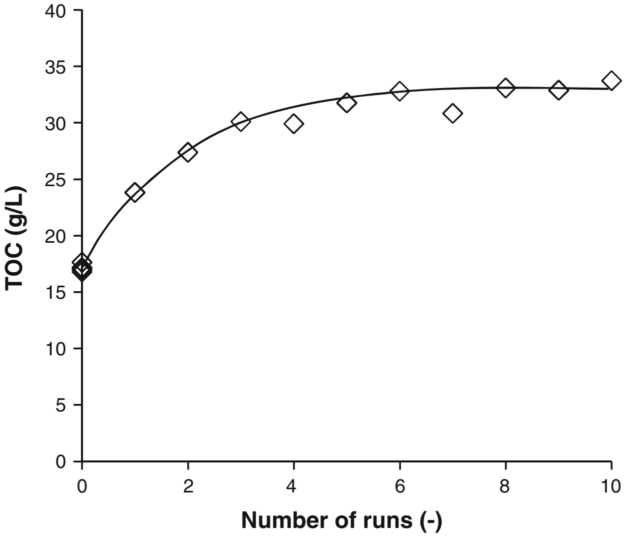

Fig. 2 TOC concentrations in the liquid (x-axis: Number of recirculation steps)

Table 5 Concentration of identified substances, TOC and C recovery (sum of C in the identified substances compared to TOC)

	Acetic acid	Glycolic acid	Formic acid	Levulinic acid	Glucose	HMF	Phenol	TOC	C recovery
Concentration in g/L									%
HTC-Ref	12.7	19	2.0	0.2	0.3	0.2	0.8	17.2	42
HTC-Recirc	33.4	4	1.0	1.3	0.9	1.3	0.0	33.2	51
Yield in g/kg									
HTC-Ref	64.0	9.4	10.2	1.0	1.6	1.1	4.1	176	
HTC-Recirc	62.9	7.7	1.8	2.4	1.7	2.5	0.0	127	

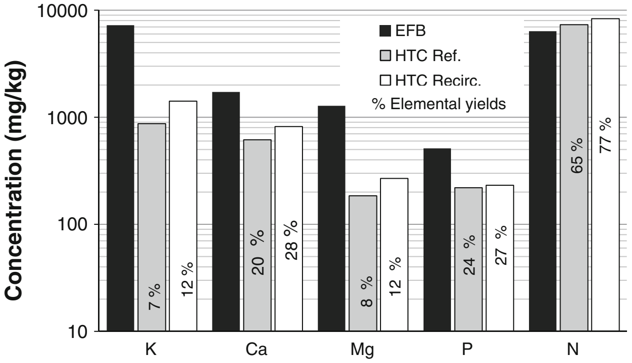

Fig. 3 Concentration of the main ash forming elements of EFB and HTC coal. Percentages indicate mass yields of specific elements in HTC coal compared to untreated EFB

Figure 3 gives a more detailed overview of the concentrations and yields of the main ash forming elements in the solid product. EFB especially contain a high K concentration. It can be noted that the concentration of K and Mg in the HTC coal is reduced by almost one order of magnitude. Ca and P show a smaller reduction whereas the concentration of N even slightly increases.

There are four pathways how inorganic substances remain in the coal. They may be organically bound, form insoluble salts, remain adsorbed to the coal or are dissolved in the liquid but remain in the coal during thermal drying. By mechanical dewatering about 94 % of the water present during the reaction can be removed mechanically. The remainder is evaporated during thermal drying. Thus for an element which is completely dissolved in the liquid, at least 6 % must remain in the coal, as its salts stay in the coal during thermal drying. When process water with dissolved salts is recirculated, the concentration in the liquid and therefore also the amount in the coal increases.

As the elemental yields of K and Mg are close to the minimal amount, presumably these elements are completely dissolved in the liquid and can be removed from the HTC coal to a very large extent. This underlines the importance of mechanical dewatering. By yielding a lower water content, next to energetic reasoning, also more minerals are separated.

Ca and P presumably form less soluble carbonates and phosphates but are dissolved to a large extent, too, which is promoted by a low pH value. Concentrations of N in the HTC coal slightly increase which was also observed in experiments with other biomass. This may indicate that N is bound in organic compounds which may be rather stable or are built into the carbon network [21].

Due to the relative increase in the concentration of Ca compared to K, the ash melting temperature also rises. Thus, relative to EFB boilers, HTC coal boilers can be operated at higher combustion temperatures and with reduced ash handling.

Simulation of an Industrial-Scale HTC Plant

This section describes the simulation of a HTC plant with a nominal capacity of 5.7 t/h EFB, producing 1.3 t/h HTC coal with a water content of 10 %. It was modelled using *Aspen Plus V7.1*. The material and energy balances from the simulation enable raw material, product and waste streams as well as auxiliary energy demand to be quantified.

Plant Design and Modelling Assumptions

The plant flow sheet is shown in Fig. 4. The EFB are first mixed with recycled process water to form a pumpable slurry (1) with a solids content of 15 % and then preheated in several stages, first with heat exchangers, then by mixing with steam recovered at different temperatures during the cooling and de-pressurizing of the HTC coal slurry. The heat recovery scheme is adapted from a pilot plant for the hydrothermal treatment of peat, the so-called Swedish Peat Process, which was operated from 1954 to 1964 in Lund, Sweden [22, 23]. The pressure levels of the de-pressurization stages are chosen so that the total amount of steam recovered in each step can be utilized in the respective mixing pre-heater. Only direct heat exchange is employed at temperatures larger than 100 °C, because decomposing biomass and condensing tar-like substances from the product would likely cause fouling and clogging in heat exchangers. The additional steam required to reach the reaction temperature is produced by a boiler (2) fired with surplus fibres and shells from the palm oil mill.

The product is mechanically dewatered (3) to a moisture content of 40 %. This is a conservative value for a high throughput industrial press, compared to the moisture content of 32 % achieved in the laboratory-scale experiments. The process water is partly recirculated to prepare the biomass slurry, while the excess leaves the plant as waste water. The waste water treatment is not included in the simulation.

The HTC coal is then dried to a moisture content of 10 % (wet basis) and pelletized. Low temperature drying is employed. To this end, the drying air is heated with steam (4) at 100 °C recovered from the HTC-coal-slurry depressurization process. The gaseous byproducts (5) from the HTC reactor consist mostly of water vapour (77 %) and CO_2 (20 %). Because they also contain 2.5 % CO, they need to be oxidized. They are therefore cooled to condense the water and then co-combusted in the boiler.

The HTC reactor is operated at 220 °C with a residence time of 4 h. The pressure of 30 bar is well above the saturation pressure to reduce the steam loss associated with the gaseous byproducts. The reactor is modelled as a black box with HTC coal yield and composition obtained from the experiments with process water recirculation described in Sect. 3. The yields of CO_2, CO, CH_4, H_2, acetic acid and

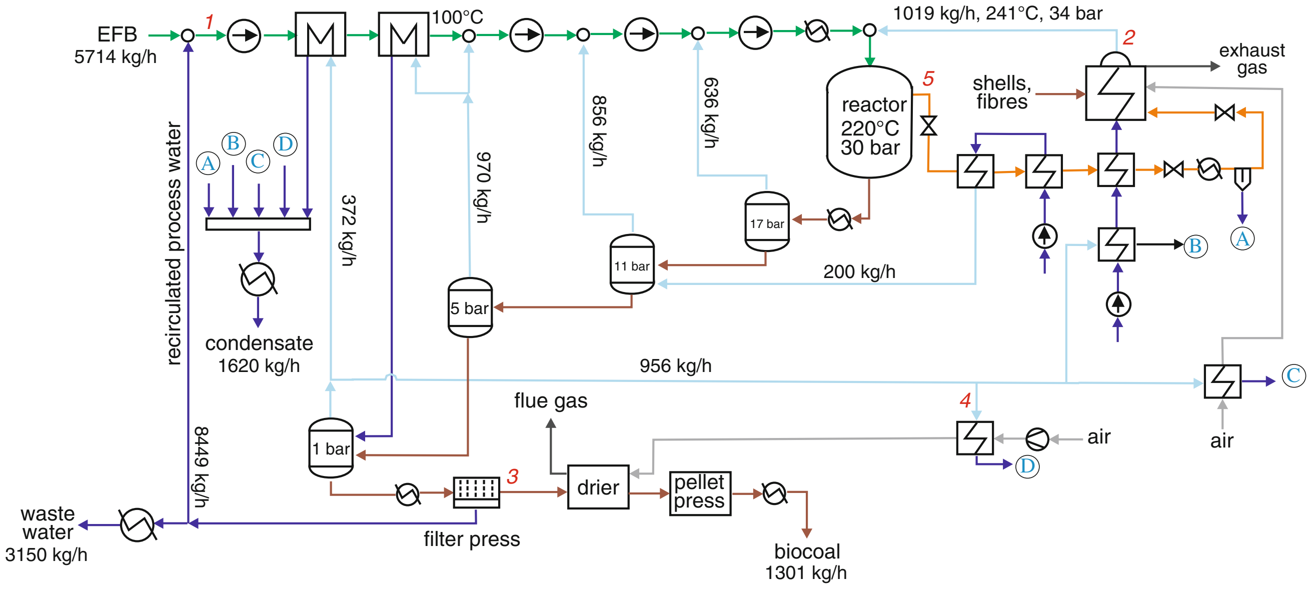

Fig. 4 Flow sheet of the simulated HTC plant

formic acid are also obtained from experiments described in Sect. 3. The remaining dissolved matter in the process water is calculated from the elemental balances for C, H, O, N, S and ash (minerals) by difference and characterized by elemental composition and calorific value only.

First scale-up experiments indicate that results from laboratory batch experiments can be reproduced on a pilot plant level in a continuous operation mode [24]. The reactor is envisaged to be designed as a plug flow reactor, where feedstock is added at the top and HTC-coal slurry is removed from the bottom. For the cost estimate, a height to diameter ratio of 5:1 is assumed.

The following assumptions regarding heat loss and efficiency are used in the simulation:

- The slurry pump efficiency is 45 %.
- Heat loss from the reactor is 8 kW (0.06 % of the EFB energy). Heat loss from the biomass slurry and HTC coal slurry are 19 kW and 21 kW, respectively, corresponding to 0.16 and 0.18 % of the EFB energy.
- Boiler and drier heat losses are 3 % of the boiler fuel and 5 % of the energy of the steam supplying the drier, respectively (25 and 35 kW).
- The boiler excess air fraction is 40 %, the fraction of unburned carbon is 3 %, and the exhaust gas temperature is 130 °C.
- The drier exhaust temperature is 10 K above the condensation temperature.
- The minimal heat exchanger temperature difference is 10 K.
- The pressure difference between flash steam and slurry in the mixing preheaters is 2 bar.
- The waste water is cooled to 40 °C before treatment
- The ambient temperature is 27 °C, the relative air humidity 80 %.
- The energy consumption of any waste water treatment is not taken into account.

Simulation Results

The resulting energy balance of the HTC plant is given in Table 6. Per MJ_{HHV} of EFB processed, 16 kJ of electricity and 67 kJ of boiler fuel are required. In a typical palm oil mill, the boiler fuel demand can easily be covered by surplus fibres and shells. However, if the mill is not connected to the electricity grid, it needs to be confirmed whether the additional electricity demand can be covered by the steam turbine of the palm oil mill.

Most of the feedstock moisture and water produced in the reaction leaves the process as waste water, which is obtained from the HTC coal dewatering, and as condensate from the flash steam. Table 7 shows amounts and organic and mineral loadings of the waste water as resulting from the simulation.

Approximately 25 % (1,219 kg/h) of the total process water can be recycled as feedwater for the steam production after treatment. The remainder has to be discharged.

The overall energetic efficiency (on HHV basis) of the process is 71.2 %, whereas 1.5 % of the energy input is electricity, 6.2 % is boiler fuel (shells and fibres) and 92.3 % is EFB. 28.8 % of the energy input is lost as organic substances dissolved in the process water and waste heat. For comparison, if the EFB were simply dried

Table 6 Energy balance

HTC-coal output (kW_{HHV})	9,131
Empty fruit bunches (kW_{HHV})	11,851
Fibres and shells for boiler (kW_{HHV})	793
Total electricity consumption (kW_{el})	187
slurry pumps (kW_{el})	62
pumps (kW_{el})	2
fans for drier and air coolers (kW_{el})	45
dewatering press (kW_{el})	13
pellet press (kW_{el})	65

Table 7 Waste water

	From dewatering	Condensate
Mass flow (kg/h)	3,149.6	1,620.0
Organics load (g/L)	91.9	7.9
Mineral load (g/L)	16.7	0.0

to a moisture content of 10 % with a thermal energy consumption of 4,000 kJ/kg evaporated water, 33 % of the EFB energy where consumed for the drying. The energetic efficiency of the HTC is therefore slightly higher than for simple drying and pelletizing of the EFB.

Economic Evaluation

The investment, operating, and total production cost of the HTC coal are calculated based on results from the simulation model. Plant capacity may have a strong impact on product cost due to economy-of-scale effects for the investment cost. The capacity of the HTC plant is dependent on the amount of EFB produced by the palm oil mill it is attached to. Palm oil mill capacities typically lie in the range of 20–90 tonnes of FFB per hour (based on data of 12 mills analyzed in [2]), resulting in 4-21 tonnes EFB per hour. However, part of the EFB may be needed for mulching the plantation, limiting the amount available for the HTC plant. Two different plant sizes were analysed: *plant-1* has a processing capacity of 5.7 t/h EFB while *plant-2* has a processing capacity of 13.8 t/h EFB. *Plant-1* represents a palm oil mill with a processing capacity of 50 tonnes of FFB per hour, where only 50 % of the EFB can be used for the HTC because the rest is used for mulching. *Plant-2* represents a large palm oil mill with a processing capacity of 60 tonnes of FFB per hour, where the complete amount of EFB is used as a feedstock for HTC. The efficiency of *plant-2* is assumed to be the same as for *plant-1*.

Calculation Methods and Assumptions

An annual capacity factor of 80 % is assumed in both cases, equivalent to 7,008 h per year of operation at nameplate capacity. It is assumed that the plant generally runs 24 h per day and 7 days a week to avoid frequent start-ups and shut-downs. The total annual consumption of EFB is 40,000 tonnes for *plant-1* and 96,700 tonnes for *plant-2*. Transportation to the harbour and shipping to Europe are included in the production costs.

Based on the simulation results, the plant equipment is sized and the module cost (purchased equipment cost plus engineering, equipment erection, piping, electrical installation and instrumentation, foundations, structural steel and process buildings) are estimated based on data from literature [25–30]. Overdesign (safety) factors of 10–20 % are applied as recommended by [31]. All components in contact with the biomass or HTC coal slurry are from stainless steel. The total capital investment (TCI) comprises the total module costs (CBM) plus fees and contingencies (15 % of CBM), offsite costs (ancillary buildings, site development, utilities), working capital, and start-up costs. The cost of land is neglected. Published equipment cost data is mostly related to North American or European locations. Such cost can be translated to a different geographical location with the help of location factors, which take into account regional conditions such as cost and productivity for labour, equipment, and taxes [32]. Location factors for Malaysia and South-East Asia are, in general, similar to those for Germany [33, 34], therefore investment cost estimates for a German location have been used without modification.

The cost estimate does not include R&D expenditures or risk premiums for a first-of-a-kind plant, and therefore represents a future commercial plant after some successful demonstration projects have been conducted.

The annual carrying charges are calculated as the annuity of TCI, taxes and insurances. Annual levelized costs for auxiliary energy, raw materials, and operation and maintenance are calculated with the constant escalation levelization factor (*CELF*) according to Eq. 2. Constant money values (year 2010 €) are used with real escalation rates of rates of 0.5 % per year (p.a.) for electricity, and 0.3 % p.a. for biomass.

$$CELF = \frac{C_l}{C_0} \cdot \frac{k(1-k^n)}{(1-k)} \cdot CRF \text{ with } k = \frac{1+r}{1+i} \tag{2}$$

C_l is the annual levelized cost, C_0 is the cost at the start of the project, *CRF* the capital recovery factor, i the interest rate and r the escalation rate of the respective type of expenses.

The main assumptions for the economic calculation are given in Table 8. Labour requirement is estimated based on data for a pyrolysis plant [35] and amounts to 3.1 plant

Table 8 Assumptions for the economic calculation

Economic plant life (a)	15
Interest rate (% p.a)	10 %
Taxes and insurances, % of TCI per year (–)	1 %
EFB (65 % moisture content) (€/t)	3.0
Fibres and shells for boiler (20 % moisture content) (€/t)	20.0
Electricity (€/MWh)	83.0
Maintenance high wear components, % of CBM (–)	10 %
Maintenance low wear components, % von CBM (–)	2 %
Chemicals, ash and waste water disposal (€/t HTC coal)	0.5
Plant operator (€/h)[a]	2.1
Biomass preparation yard worker (€/h)[b]	0.5
Shipping cost (16.000 km by Handysize dry bulk carrier) (€/t)	35.8
Loading/unloading of HTC coal (€/m^3)	0.5
Pellet transport by truck from palm oil mill to harbour (100 km) (€ t^{-1} km^{-1})	4.8

[a] based on salary for technician in Malaysia [36, 37]

[b] based on salary for plantation worker in Malaysia [38]

operators and 1.05 unskilled workers for biomass preparation per shift for *plant-1*. For *plant-2*, 4.0 operators and 1.6 workers are required.

Results

The investment cost of *plant-1* and *plant-2* are summarized in Table 9, the resulting levelized production costs per GJ$_{HHV}$ of HTC coal are shown in Table 10.

The production cost is 19 % lower for the bigger *plant-2* due to economy-of-scale effects. The biggest cost component by far are the carrying charges (52–57 %), followed by shipping to Europe (15–18 %), maintenance costs (11–12 %), and cost of the EFB (5–7 %).

The total cost of the HTC coal, including shipping to Europe, amounts to 7.94 and 9.67 €/GJ$_{HHV}$ for *plant-1* and *plant-2*. For comparison, industrial wood pellets ranged between 114 and 140 €/t between 2007 and 2010 [11], corresponding to 6.54–7.96 €/GJ$_{HHV}$. For HTC coal pellets to be competitive with bituminous coal priced at about 2.6 €/GJ$_{HHV}$, public policy incentives, such as carbon certificates, are required.

Since no commercial HTC plants are yet in operation, there remains a high degree of uncertainty regarding the investment cost.

Shipping prices are highly volatile due to the supply and demand of shipping capacity. For example, between 2004 and 2008 the charter rates for Capesize vessels rose five-fold due to a shortage in shipping capacity [39]. Shipping costs are also strongly dependent on the size of ships that can be employed and whether a well established trade route is used [39]. With shipping contributing more than 15 % of the total cost of the HTC coal, developments in the trade of dry bulk goods between South-East Asia and Europe may well prove crucial for the economic viability of HTC coal from EFB.

Alternatively, burning the HTC coal in power plants in South-East Asia may become an interesting option given that public policy support is implemented.

Table 9 Capital investment for HTC *plant-1* (40.0 kt/a EFB) and *plant-2* (96.7 kt/a)

	Cost *plant-1* (Mio €)	Cost *plant-2* (Mio €)
Reactor	1.69	3.51
Slurry pumps	0.56	1.01
Flash tanks	0.54	1.00
Filter press	0.74	1.39
HTC coal drier	0.78	1.27
Pellet press	0.34	0.62
Pellets coal storage & handling	0.17	0.30
Screw feeder and slurry preparation	0.09	0.15
Heat exchangers	0.43	0.62
Coolers	0.35	0.54
Pumps and fans	0.04	0.05
Utility boiler	0.25	0.51
Waste water treatment	0.29	0.49
Biomass sizing and sorting	0.11	0.20
Ancilliary buildings	0.23	0.40
Site development	0.11	0.20
Utilities	0.23	0.40
Fees & contingencies	0.96	1.75
Start-up cost	0.20	0.36
Working capital	0.12	0.24
Allowances for funds used during construction	0.79	1.44
Total capital investment (TCI)	9.01	16.47

Table 10 Levelized cost (delivered at European harbour)

	Levelized cost *plant-1* (€/GJ$_{HHV}$ HTC coal)	Levelized cost *plant-2* (€/GJ$_{HHV}$ HTC coal)
Carrying charges	5.50	4.16
Labour	0.26	0.14
Maintenance material	1.13	0.85
EFB	0.53	0.53
Shells for boiler	0.09	0.09
Electricity	0.49	0.49
Other operating cost	0.02	0.02
HTC coal truck transport	0.22	0.22
HTC coal shipping to Europe	1.44	1.44
Total HTC coal cost (at European harbour)	9.67	7.94

Environmental Impact

Waste water handling, the nutrient balance of palm oil harvesting, and the GHG balance appear to be the principal environmental aspects when employing HTC at palm oil mills.

Waste Water

The waste water from the HTC coal dewatering carries a high load of organic and mineral compounds. Short chain organic acids, including formic and acetic acid, which are present in high concentration, can be readily treated by anaerobic digestion. Wirth [40] achieved methane rates of up to 650 L/kg of TOC for waste water from maize ensilage HTC. Thus anaerobic treatment of process water together with POME may well increase the methane yield. However, phenol and 5-hydroxymethylfurfural were also detected in the process water. These substances are more persistent and are known to have inhibiting effects on microorganisms [41]. A subsequent aerobic treatment step therefore seems to be necessary even if anaerobic treatment is employed. On a carbon basis, only half of the dissolved substances in the liquid could be detected by HPLC, and the liquid is expected to contain a large number of further compounds. These may well include persistent organic pollutants and substances which are hazardous to waters.

The HTC waste water also contains 20–90 % of the minerals of the EFB. If the waste water is treated to destroy harmful organic substances, it is conceivable that the treated waste water, which still contains the dissolved minerals, can be applied to the plantation as fertilizer.

The treatment of HTC waste water is an issue which requires further research. Discharge of the waste water to the POME ponds or river systems as well as application to the soil without adequate treatment must be avoided.

Nutrient Recovery

When EFB are used for mulching, nutrients are returned to the plantation. When the EFB are converted to HTC coal instead, these nutrients have to be replaced by mineral fertilizers. This replacement has an impact on both GHG balance (see next section) and economic performance.

According to [2], the net return from EFB used for mulching is 4.45 €/t (14.4 RM/t) taking into account the fertilizer value, the cost associated with its application and the increased FFB yield. [42] calculates a significantly higher fertilizer value of approximately 9.5 €/t EFB on a wet basis wb for an Indonesian location. The fertilizer value of the EFB can be interpreted as cost of redeploying this resource. The price of 3 €/t EFB assumed in the calculation of the HTC coal production cost in Table 10 is based on actual prices at which EFB are offered for sale, which can be as low as 2.1 €/t [7].

For the EFB used in the carbonization experiments (see Fig. 3) we calculated the fertilizer value of the EFB at 1.54–4.09 €/t on a wet basis with fertilizer prices for N, P, K, Ca, Mg from [2] and [42]. The fertilizer value lost through the export of HTC coal amounts to 0.7–1.3 €/t EFB on a wet basis, while the remaining nutrients stay with the waste water and might be recoverable with adequate treatment.

These calculations do not account for any other beneficial effects of the EFB mulching, such as improved soil structure and moisture retention, and resulting influence on FFB yield. When a decision has to be made between HTC and mulching, such site specific factors should be taken into consideration.

When the EFB are dumped rather than mulched, the fertilizer value is not utilized. Replacing dumping by HTC may improve the nutrient balance given that nutrients can be recovered from the waste water.

Greenhouse Gas Emissions and Avoidance Costs

EFB dumping causes significant greenhouse gas (GHG) emissions due to the formation of methane under anaerobic conditions. If the EFB are utilized for HTC instead, these emissions are avoided. A further reduction of GHG emissions can be credited to the substitution of fossil coal by renewable HTC-coal as a power plant fuel.

The annual methane emissions of the EFB dumping were calculated with the IPCC default method (tier 1) [43] assuming a methane correction factor of 80 % for solid waste disposal sites with a depth of more than 5 m, a fraction of 50 % methane in the generated gas, and a fraction of dissimilated degradable organic carbon of 50 % [44]. The resulting methane emissions amount to 45.9 kg/t EFB_{wet} on a wet basis, which corresponds to GHG emissions of 1,148 kg CO_{2eq}/t EFB_{wet} using a GWP100 of methane of 25 [45].

Regarding the electricity consumed by the HTC plant, specific GHG emissions of 890 kg/MWh_{el} are assumed, based on the average of the Malaysian power mix [46]. This value would apply if electricity is taken from the grid. If electricity is produced on-site by combustion of shell and fibres, the value can be lower or even zero.

Regarding transport emissions, $339.8\,g_{CO_2}/(t\,km)$ are assumed for truck transport and $8.9\,g_{CO_2}/(t\,km)$ for transport by ship [47]. GHG emissions from HTC coal production, the avoided emissions by not dumping the EFB, and by replacing fossil bituminous coal in a power plant are given in Table 11. Potential GHG emissions from the treatment of waste water are not taken into account.

Table 11 GHG emissions from HTC coal production and transport and avoided GHG emissions from EFB dumping and bituminous coal combustion

	Emissions of HTC coal production (kg $CO_{2eq}/GJ_{HHV,\ HTC\ coal}$)
Grid electricity	5.06
Truck transport	1.34
Shipping to Europe	1.87
Avoided emissions	
EFB dumping	199.48
Substitution of bituminous coal in a power plant	89.06
Avoided supply chain emissions of bituminous coal [47]	12.35
Net avoided emissions	288.84

The net avoided emissions amount to 67,400 t/a for *plant-1* and 163,400 t/a for *plant-2*, of which 65 % are related to the prevention of EFB-dumping, while most of the remainder accrues to the substitution of bituminous coal.

For the HTC coal to be economically viable, the cost of CO_2 avoidance has to be covered in some way. The avoided emissions from the dumping of the EFB may be monetarized by carbon credits issued under the Clean Development Mechanism (CDM). In the European fuel market, the HTC coal can either compete with bituminous coal plus carbon certificates from the European Union Emission Trading Scheme (EU ETS), or it can compete with industrial wood pellets and be treated as biomass according to feed-in tariffs or renewable energy certificates trading schemes.

If the HTC coal is used to replace bituminous coal, the cost of CO_2 avoidance c_{CO_2} is defined according to Eq. 3 as the difference in cost between HTC and bituminous coal (€/GJ) divided by the difference in specific GHG emissions caused by the production and use of each (t/GJ):

$$c_{CO_2} = \frac{c_{HTCcoal} - c_{bit.coal}}{GHG_{bit.coal} - GHG_{HTCcoal}} \qquad (3)$$

with a bituminous coal price of 2.567 €/GJ_{HHV}, this results in CO_2 avoidance costs of 24.6 €/t_{CO_2-eq} for *plant-1* and 18.6 €/t_{CO_2-eq} for *plant-2*.

The avoided methane emissions from not dumping EFB constitute the biggest share of the GHG reduction. These emissions, however, are much lower when HTC replaces the use of EFB for mulching. If HTC replaces mulching, the fertilizer value of the EFB has to be replaced by mineral fertilizer and the GHG emissions related to the fertilizer production need to be accounted for. For the EFB used in the carbonization experiments and specific emissions for the mineral fertilizer production from [48], we calculated 1.917 kg $CO_{2eq}/GJ_{HHV,\ HTC\ coal}$ of which approximately 40 % can be avoided if nutrients can be recovered from the HTC wastewater. The total supply chain emissions of the HTC coal production and transport in this case amount to 9.4–10.2 kg $CO_{2eq}/GJ_{HHV\ HTC\ coal}$, which is in the same range as the supply chain emissions of bituminous coal. The avoided emissions are limited to the direct emissions from combustion of the bituminous coal replaced by biomass. The resulting CO_2 avoidance costs are 79.8 €/$t_{CO2\text{-}eq}$ for *plant-1* and 60.4 €/$t_{CO2\text{-}eq}$ for *plant-2*.

The current CO_2 prices of 8 €/t for EU ETS Emission Reduction Units and 5 €/t for the Certified Emissions Reductions from CDM (March 2012) are not sufficient to make HTC coal competitive with bituminous coal. However, in order to achieve a long term stabilization of atmospheric CO_2 concentrations below 450 ppm, marginal costs of CO_2 avoidance of over 50 €/t in 2030 and between 100 and 200 €/t in 2050 are expected [49]. For comparison, CO_2 avoidance costs for carbon capture and storage (CCS) from coal fired power stations are estimated at 42 €/t CO_2 on average [50], for electricity from biomass at 40–57 €/t, and for wind power at 55–104 €/t [51]. In this context, HTC with avoided EFB dumping offers a relatively low cost mitigation.

When compared to industrial wood pellets, HTC-coal from *plant-2* is already in the same price range without adding in carbon credits (see Sect. 5.2). If credits for avoided emissions from EFB dumping are included at 10 €/$t_{CO2\text{-}eq}$, the net resulting HTC coal cost are 7.80 €/GJ_{HHV} for *plant-1* and 6.07 €/GJ_{HHV} for *plant-2*, compared to a market price for wood pellets of 6.54–7.96 €/GJ_{HHV}. Combustion of wood pellets and other biomass is not covered by the EU ETS, but by country-specific feed-in tariffs or renewable energy certificates. Currently, co-combustion of biomass in coal-fired power stations is common in Belgium, the Netherlands and the UK due to their renewable energy certificates schemes. Since the cost of HTC coal pellets are in the same range as industrial wood pellets, their use for co-combustion will be economically viable under the same circumstances.

Discussion and Conclusions

This paper examines the use of EFB from palm oil production as a feedstock for hydrothermal carbonization. The first part of this paper reports experiments with a sample of EFB from Sumatra. Experiments were performed with both de-ionized water and with recirculated process water at 220 °C.

Raw EFB have a relatively high hydrogen content and a HHV of 21 MJ/kg. With hydrothermal carbonization, the

HHV is increased to over 27 MJ/kg. By recirculating the process water, the amount of carbon in the liquid byproduct is decreased from 18 to 13 % and the solid carbon yield is increased from 74 to 77 %. In this case the HHV of the HTC coal is 28 MJ/kg and the energetic process yield is 77 % based on the HHV. HTC coal can be dewatered mechanically to a water content of 32 %. The dissolved component with the highest concentration is acetic acid with a yield of 6 %. K is completely dissolved in the liquid whereas 70 % of N remains in the coal. Mainly by altering the reaction temperature, HTC coal characteristics can be tuned within a certain range. An increase in temperature leads to a higher calorific value but lower yield of HTC coal. Due to this trade-off between product quantity and quality, the optimum process conditions depend on the elasticity of the attainable market price for HTC coal with respect to its quality. Therefore process optimization is a promising yet complex task, as sensitivities of reaction temperature regarding a series of parameters (including production, logistics and utilization of the HTC coal) must be identified.

These laboratory-scale experimental results were used as an input to a simulation model of an industrial-scale HTC plant with a capacity of processing 5.7 t/h EFB (11.85 MW_{HHV}). The simulation results indicate an auxiliary energy consumption of 187 kW (16 kJ/MJ EFB) of electricity and 793 kW (67 kJ/MJ EFB) of boiler fuel for steam production. The demand for boiler fuel can be covered by surplus fibres and shells from the palm oil mill. If the palm oil mill is not grid-connected, it has to be confirmed whether the electricity demand of the HTC plant can be covered by the steam turbine of the palm oil mill. The HTC plant produces a total of 4.8 t/h waste water and condensate with a high load of organic and mineral compounds. Some of these substances are valuable nutrients, and their recovery and application to the oil palm plantation should be investigated. On the other hand, the waste water contains persistent organic pollutants which may present severe risk to human health and to ecosystems when discharged to the POME ponds or applied to the soil without adequate treatment. Remedial treatment and monitoring are therefore essential.

The simulation allowed equipment to be sized and investment costs to be estimated. The annual levelized production costs of the HTC coal pellets were calculated. The calculations were performed for *plant-1* with a capacity of 5.7 t/h EFB and *plant-2* with a capacity of 13.8 t/h. The TCI is 9 million € for *plant-1* and 16.5 million € for *plant-2*. The cost of HTC coal production then amounts to 7.9–9.7 €/GJ_{HHV}, including shipping to Europe. The biggest cost component is the recovery of capital investment. If carbon credits at a value of 10 €/t CO_2 are credited for methane emissions avoided from not dumping of the EFB, the net HTC coal pellet costs reduce to 6.1–7.8 €/GJ_{HHV}. For comparison, the market price of industrial wood pellets currently lies in the range of 6.5–8.0 €/GJ_{HHV}.

Biomass co-fired in coal-fired power stations does not qualify for renewable energy feed-in tariffs in most European countries. In this case, the HTC coal has to compete against fossil coal plus carbon certificates. If carbon credits from avoided methane emissions and from substituting bituminous coal are taken into account, a carbon price of 19–25 €/t CO_2 would be required to become profitable. If only the emission reductions from substituting bituminous coal are credited, the required carbon price is as high as 60–80 €/t CO_2. In jurisdictions where co-firing of biomass with fossil coal is not supported by feed-in tariffs or renewable energy certificates, the economic viability of co-firing HTC coal therefore is largely dependent on carbon credits for avoided GHG emissions at the palm oil mill. When HTC replaces the dumping of EFB, this results in avoided methane emissions of 199 kg $CO_{2eq}/GJ_{HHV,\ HTC\ coal}$. However, this is not so when the baseline scenario is using the EFB for mulching the oil palm plantation, which is also a common practice.

There are no commercial HTC plants in operation and the best available data for the HTC reaction is currently based on laboratory-scale batch experiments. This means that there remains a large uncertainty with regard to HTC performance and cost. Optimization of the design and operating parameters of the HTC plant may well yield higher efficiencies and lower production costs. On the other hand, technical issues like biomass pressurizing and waste water treatment might increase the costs.

The general design of the process flowsheet for the simulation is based on a pilot plant for the hydrothermal treatment of peat which was operated in Sweden from 1954 to 1964. Funke and Ziegler [52] discuss the feasibility of the technical implementation of HTC, based on the literature about peat processing plants and experience with certain plant equipment from other biomass processes which is transferable to HTC. They come to the conclusion that a technical realization is possible today, but optimization of process equipment is required to improve process economics. They identify the feeding system, heat recovery system and waste water as key areas where more R&D is required. In the last few years, several HTC pilot plants have started operation in Germany, but so far no data on long-term continuous operation is available.

Better integration with the palm oil mill may significantly reduce the investment cost, since steam for the HTC reactor can be taken from the boiler of the palm oil mill, assuming this operates at the required pressure. Using heat from the HTC process for FFB sterilization may allow the preheating scheme of the HTC to be simplified and thereby reduce the complexity and investment cost of the HTC plant.

HTC shows potential for treating EFB and thereby avoid the GHG emissions from EFB dumping. However, technically simpler and more developed technologies have been suggested, such as composting [6, 9] or briquetting [7] the EFB. HTC needs to be evaluated against these other options. Both composting and briquetting have been successfully tested in research projects but are not common practice. While in this paper we only consider the EFB, the liquid palm oil effluents (POME) also cause significant methane emissions and pose an unsolved waste problem. Therefore, integrated concepts which deal with both the EFB and POME waste streams could be especially attractive.

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